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Farmed animal production in tropical circular food systems

by
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Marion de Vries
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Contents

Abstract

In the discourse about the development of farmed animal production (terrestrial livestock production and aquaculture) in the tropics, two important food system outcomes emerge: (i) to supply animal-sourced food (ASF) at a level that suffices healthy future diets, including for poor people; and (ii) to contribute to climate change mitigation and minimize pollution with nitrogen and phosphorus. Livestock production and aquaculture contribute to food security directly by increasing producers' food diversity and availability, but also that of urban consumers, but also indirectly through income generation and increased farm resilience. Recently, circularity has come to the fore as an integrated approach to food system development. Circularity has four cornerstones: (i) food crops have highest priority (which implies no competition between food and feed); (ii) avoid losses; (iii) recycle waste; and (iv) use animals to unlock biomass that humans cannot eat. In this review, the role of farmed animals in circular food systems in the tropics is presented in four case studies, and the impacts of circularity on food security and environmental impact mitigation are discussed. The cases are ruminants in grazing systems in West Africa and in Colombia, fish in pond aquaculture in general, and land-limited dairy production in Indonesia. Additionally, options for novel protein sources for use in livestock and fish feeding are presented. It is concluded that farmed animals are important in circular food systems because of their use of land unsuited to crop production, their upgrading of crop residues, and their supply of manure for crop production. Nevertheless, the increasing demand for ASF puts pressure on important characteristics of circularity, such as minimizing food-feed competition, maximizing use of waste streams in feed, and the value of manure for fertilization. Hence, in line with conclusions for Western countries, maximum circularity and sustainability of food systems can only be achieved by optimizing the population size of animals. Hence, a sustainable contribution of ASF production to global food security is complex, and not only a technical matter or outcome of an economic process balancing supply and demand. It requires governance, for which public, private and social actors need to partner.

Keywords: Livestock production, aquaculture, climate change mitigation, pollution, farming systems

1. Introduction

Farmed animal production, which includes terrestrial livestock production and aquaculture, is part of food systems. A food system *"encompasses the entire range of actors and their … activities involved in the production, aggregation, processing, distribution, consumption and disposal of food products that originate from agriculture, forestry or fisheries, and parts of the broader economic, social and natural environments in which they are embedded"* (Van Berkum et al. 2018).

Food system outcomes relevant for the production of animal-sourced foods (ASF) are food security and environmental impacts. Food security implies that ASF are supplied and accessible at a level that suffices healthy future diets, including for poor people (Oosting et al. 2014)). The rising demand for ASF in tropical regions is an important issue for food security and will be addressed in section 1.1. Major environmental isues are greenhouse gas (GHG) emissions (Gerber et al. 2011; Özkan et al. 2015; World Bank 2019), and many countries have included farmed animal production interventions in their Intended Nationally Determined Contributions (FAO 2018), pollution with nitrogen (N) and phosphorus (P), and land and water use (World Bank 2019). Some background information about the environmental issues associated with ASF production is presented in box 1. Section 1.2 will compare the impacts of GHG emissions and land use among different ASF and plant-sourced foods.

Box 1. Environmental issues and ASF (adapted from World Bank 2019)

Environmental issues associated with production of ASF fall into three categories:

Land and water use: Within agriculture, ASF production is the largest user of land and water resources. The sector uses most of the world's grasslands and more than a third of the world's arable land for feed production, as well as the irrigation and rainwater used on those lands. Livestock uses these resources predominantly for feed production, with four broad impact pathways:

1. conversion of forests and other natural vegetation to feed-crop land and pasture results in loss of biodiversity, depletion of aquifers, and GHG emissions (when soil organic matter turns into carbon dioxide and methane);
2. competition with food crops for land and water. Of the world's 2 billion ha of grassland, one third could potentially be used as cropland. Feed production uses about a third of agricultural water. Livestock production is generally less efficient than crop production in terms of production of human food per unit of arable land. This affects the efficiency of food systems and limits use for other potential functions;
3. terrestrial livestock production can cause land degradation. Overgrazing affects vegetation cover and potentially results in productivity losses, soil erosion, carbon losses and adverse impacts on biodiversity and water cycles. Land degradation can also be a long-term process, when nutrients extracted from the soil by grazing or feed production are not replenished – for example, by fertilization; and
4. pollution of water and land resources by pesticides, chemicals and other unwanted substances such as metals and organic residues ending up in the ecosystem. These may affect flora and fauna, fisheries, recreation and drinking water.

GHG emissions: Emissions from ASF production have been estimated to contribute 14.5 per cent of global anthropic emissions of GHG. The largest contributor is methane (about 44 per cent when expressed in CO_2 equivalents), followed by nitrous oxide (29 per cent) and carbon dioxide (27 per cent). Emissions from ASF production account for 44 per cent of global anthropogenic methane, 53 per cent of global anthropogenic nitrous oxide and 5 per cent of global carbon dioxide emissions. Four major sources of GHG emissions from livestock production occur:

1. emissions from the production, processing and transportation of feed, accounting for about 45 per cent of all ASF-related GHG emissions;
2. enteric methane emissions from the rumen of cattle, sheep and goats during the digestion of feeds (about 40 per cent of emissions, 77 per cent of which comes from cattle);
3. emissions associated with land-use change (see above) (<10 per cent of emissions); and
4. emissions from manure storage and handling, which generate methane and, more importantly, nitrous oxide emissions (about 10 per cent of all ASF-related emissions). Fishponds with anaerobic conditions in the sediment may also emit methane and nitrous oxide.

N and P pollution of land, water and air: N and P are important nutrients for crops, grasslands and livestock. In agricultural systems, these nutrients cycle from soil to crops and grass, to livestock via feed, and back to the soil via manure. Ideally, these nutrient cycles happen with minimal losses. When substantial, losses can cause N and P pollution that results in: (i) eutrophication (excessive growth of algae in water) that may lead to “dead zones” in aquatic systems; and (ii) acidification of rain and soils that may affect vegetation and aquatic life. Most N and P losses from livestock production are either associated with animal manure management or with the fertilization of feed crops and grazing lands. They take place at three stages of the supply chain:

1. manure collection and storage (for processing and/or recycling), when N and P may be lost as gaseous components or may leach away – the liquid part of manure is occasionally discarded into the environment, causing severe pollution of water, air and soils;
2. processing of manure and slurry (manure mixed with urine) through drying, composting, biogas production, mixing into compound fertilizers, incineration and aerobic treatment – this can improve N and P recycling and thus be beneficial to the environment. Done improperly, processing contributes to N and P losses; and
3. application of manure and synthetic fertilizer to crops and grasslands may result in N and P losses through leaching, run-off and volatilization – losses may result from high application rates and poor phasing with plant uptake.

One additional food system outcome for which farmed animals are important is inclusiveness. Farmed animals have many roles and functions in farming systems. Beyond food production, they have cultural and societal functions such as for dowry, and sacrifices during religious festivities; they have financial and insurance functions, which are specifically important to poor people; they may provide a regular small income to women and children in a household; and they may provide status (Moll et al. 2007; Oosting et al. 2014; Rao et al. 2021; Udo et al. 2011). Such functions of farmed animals are most important in subsistence farming systems. The development of farmed animal production into market-orientated production will impact such functions and, consequently, vulnerable groups.

1.1 Food security: Rising demand for animal-sourced foods

Farmed animal production contributes to human food security; for many people in low- and middle-income countries, milk, fish and eggs are frequent components of the daily diet. Meats, such as beef, pork, mutton and poultry meat, are often consumed less frequently – for example, only at festivities. Rising incomes shift consumption from plant-sourced food to ASF. ASF has a high income elasticity of demand (International Food Policy Research Institute 2017), which implies that an increase in income brings about a considerable increase in demand (Speedy 2003). Specifically in low-income countries, the rise in ASF consumption per unit increase in income is high, as illustrated in figure 1 for countries in Asia. With rising gross national product, the consumption of ASF increases, plateauing at a level of 50-60 grams of animal protein consumed per capita per day.

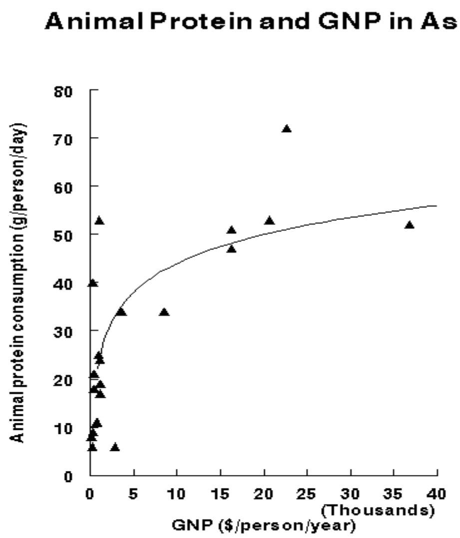

Figure 1: Gross national product (GNP) and animal protein consumption in Asian countries

Source: FAO (2020a)

Urban dwellers eat diets with a higher proportion of ASF than rural dwellers. As the rate of urbanization is high in many tropical regions, urbanization also increases demand for ASF, and so does population growth (Pica-Ciamarra and Otte 2011).

It could be questioned whether this rising demand should be met. Potentially, human beings can live without consuming ASF, though balancing nutrient supply from vegan diets requires knowledge and access to a diverse food basket. This is often not the case for poor people. Hence, many countries have included ASF in their National Dietary Recommendations (NDRs; FAO 2018). The NDRs are country-specific dietary guidelines that address public health and nutrition priorities and accessibility of foods. Nutritional reasons for including ASF in NDRs are that ASF provide proteins with a high bioavailability and an amino acid profile meeting human requirements (Elmadfa and Meyer 2017), and that they are important sources of micronutrients such as zinc, selenium, iron, vitamins A and B12, and folic acid (Beal et al. 2021; Biesalski 2005), specifically for the world's poor people (Adesogan et al. 2020). Aquatic ASF are also a good source of highly unsaturated fatty acids. Meeting NDRs for a whole population will prevent nutrient deficiencies, also for poor people. Aquaculture and livestock production may benefit the food security of poor farmers directly by providing ASF for household consumption, but also indirectly as a source of income with which additional food can be purchased, and by diversifying farms and thus increasing resilience of food production (Abu Hatab et al. 2019; Ahmed and Waibel 2019; Fraval et al. 2020; Megersa et al. 2014).

On the other hand, ASF can be overconsumed. Matena (2018) compared actual daily consumption of dairy, eggs,and meat by diverse income strata and found that: (i) poor strata consume considerably less than the NDRs in Africa and Asia; and (ii) rich strata consume approximately according to NDRs in Africa (with overconsumption in some countries), but they overconsume on all other continents. Over- and underconsumption of ASF may occur concomitantly within the same country. Overconsumption of ASF is unhealthy, especially of ASF derived from terrestrial livestock, because the fat in ASF is rich in saturated fatty acids, and high ingestion of such saturated fatty acids may cause hypercholesterolemia and cardiovascular diseases (Muehlhoff et al. 2013). Hence, meeting NDRs with ASF is partly a matter of distribution, though sub-Saharan Africa (SSA) and South and South-East Asia (SSEA) have, on average, a considerable gap between actual average consumption and NDRs for dairy and eggs, and in some countries for meat. Hence, future food systems in SSA and SSEA will require production of ASF at levels that are higher than those of today to achieve nutrition security for many poor people. However, associated with this requirement, a discourse has developed about the sustainability of such future ASF production because of its impacts on the environment and on the use of natural resources, including land and water.

1.2 Environmental issues associated with farmed animal species and their products

The environmental issues associated with ASF production, as outlined in box 1, depend on the farming system and on farmed animal species kept. Table 1 presents GHG emissions and land use associated with ASF and some plant-sourced foods, as derived from a meta-analysis of published life-cycle assessment studies of agricultural production by Poore and Nemecek (2018). Ruminant meat production has the highest mean GHG emission intensities (emission of GHG expressed as CO_2 equivalents per 100 g of protein produced), followed by milk production (represented by cheese in table 1), fish, pig and poultry production. All ASF have higher GHG emission intensities than plant-sourced food products. The variation in emission intensities (for which the difference between the mean and the 10th percentile is used as a proxy) for ASF is high, indicating that there are farms with low and farms with high emission intensities. This implies that there is room for GHG emission mitigation by addressing farms with high GHG emission intensities. One important determinant of GHG emission intensities within an ASF product is the production per animal. A high production per animal implies that the emissions associated with the animal’s maintenance are diluted across many litres or kilograms of produce (Gerber et al. 2011), which is not the case for animals with a low production. An example of the relationship between production per animal and GHG emission intensity for milk production is given in figure 3.

Land use is also higher for ruminant ASF than for plant-sourced foods, whereas fish, pigs and poultry are at an equal level with plant-sourced foods with highest land use (table 1). It is important to realize that ruminant meat and milk are often produced on lands unsuited for crop production, whereas intensive fish, pig and poultry production requires relatively high-quality feeds grown on crop lands that could have been used for human food crops directly.

Table 1
Greenhouse gas emissions and land use associated with production of protein-rich foods

Protein-rich foods	*Greenhouse gas emissions (kg CO_2-e/100 g protein)*		*Land use (m^2/year/100 g protein)*	
	Average	*10th percentile*	*Average*	*10th percentile*
Animal-sourced foods				
Beef	50	20	164	42
Lamb and mutton	20	12	185	30
Cheese	11	5.1	41	4.4
Pig meat	7.6	4.6	11	4.8
Fish (farmed)	6.0	2.5	3.7	0.4
Poultry meat	5.7	2.4	7.1	3.8
Eggs	4.2	2.6	5.7	4.0
Plant-sourced foods				
Tofu	2.0	1.0	2.2	1.1
Groundnuts	1.2	0.6	3.5	1.8
Peas	0.4	0.3	3.4	1.2
Nuts	0.3	-2.2	7.9	2.7
Grains	2.7	1.0	4.6	1.7

Source: Poore and Nemecek (2018)

1.3 ASF production in circular food systems

Recently, circularity has come to the fore as an integrated approach to develop food systems sustainably. Circular food systems are food systems with four important cornerstones. They: (i) use arable land and water bodies primarily to produce food for direct human consumption; (ii) avoid or minimize food losses and wastes; (iii) recycle by-products (such as crop residues, co-products from processing, manure, excreta), inevitable food losses and waste streams back into the food system; and (iv) use animals to unlock biomass with low opportunity costs for humans into value-food, manure and ecosystem services. As a result, circular food systems apply practices and technologies that minimize the input of finite resources (e.g. phosphate rock, fossil fuel and land), encourage the use of regenerative ones (e.g. wind and solar energy), prevent leakage of natural resources from the food system (e.g. of N and P), and stimulate recycling of inevitable resource losses in a way that adds the highest value to the food system (De Boer and van Ittersum 2018; Van Zanten et al. 2019).

Farmed animals have a role in circular food systems: waste stream biomass can be used as feed, and farmed animals provide manure and pond sediment which can be used as fertilizer to maintain or improve soil quality. The use of waste streams for feed may reduce the need for feed production with associated GHG emissions, land and water use, and N and P pollution. Maximization of the use of manure and pond sediment for fertilization may prevent losses of these nutrients. Figure 2 illustrates the flow of biomass in a circular food system.

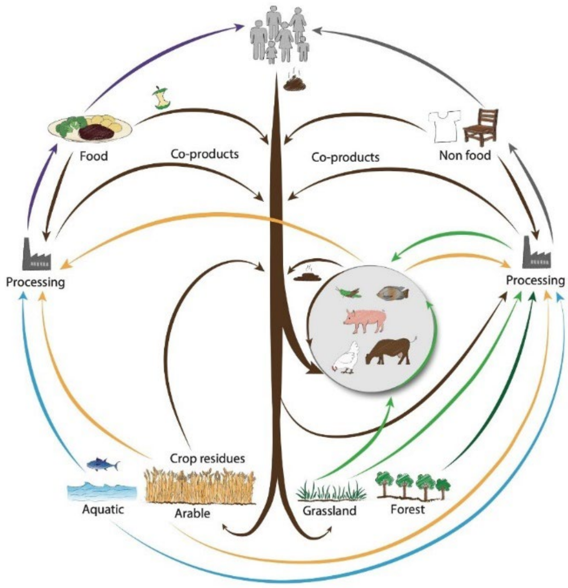

Figure 2: Flow of biomass in a circular food system

Source: Muscat (2021)

The increasing demand for ASF drives intensification of farmed animal production. Improved feeding is an important intervention to achieve this intensification. Hence, cultivation of feed crops such as maize and soybean, and of improved forages, is increasing. This, however, often happens on land which is suitable for cultivation of human food crops. Since circular food systems should use arable land for production of human food crops and not for feed crops, intensification has a trade-off with circularity of food systems. This is being referred to as food-feed competition.

Studies by Van Hal (2020), Van Kernebeek et al. (2014) and Van Zanten et al. (2019) indicate that protein consumption from ASF could be maintained at levels between 7 g and 36 g per capita per day, if livestock and fish would only consume feeds from waste streams and from lands (and water bodies) unsuited for human food crop production. Present protein consumption from ASF is close to 60 g per capita per day in wealthy countries (see figure 1). Circular food systems will, therefore, imply reduced ASF consumption in wealthy countries, which complies with dietary adjustments proposed to achieve healthy diets in the EAT-Lancet report (Willett et al. 2019).

1.4 Objective of this paper

Hence, under reduced ASF consumption scenarios, circular food systems with farmed animals have the potential to meet the food system outcomes of sufficient ASF production and minimal environmental impacts concomitantly (De Boer and van Ittersum 2018; Van Hal 2020; Van Zanten et al. 2016). It is, however, yet to be explored to what extent production systems with farmed animals have this potential in the tropical regions of SSA, SSEA and Latin America and the Caribean (LAC). The present review, therefore, will explore this potential. In the exploration the dilemma will be presented between intensification of ASF production to meet objectives of increasing ASF supply, on the one hand, and climate change mitigation and increased circularity, on the other. Since circularity of food systems implies avoidance and recycling of wastes, a circular food system will have limited N and P pollution. In addition, circular food systems will prioritize resource use for food crop production over other uses and, therefore, have limited food-feed competition.

In section 2 we describe the major farmed animal species and the farming systems they are found in. In section 3 we give examples of present and possible contributions of farmed animals and farming systems to circularity in food systems. In section 4 we address the potential of novel proteins that support the role of farmed animals to meet the objectives of sufficient ASF production and minimal environmental impacts in circular food systems. Section 5 contains the discussion and conclusions.

2. Farmed animal species and livestock farming systems in tropical regions

2.1 Major farmed animal species

Different species of farmed animals are found in different farming systems with different ASF output levels and impacts on the environment. Development trends of farming systems affect the performance of farms regarding these objectives.

In this review we consider the following farmed animal species:

Cattle: Cattle are kept for meat production, referred to as beef cattle, and for milk production, referred to as dairy cattle. Cattle do, however, have important additional functions too: draught power for land preparation, production of manure for crop fertilization, capital asset, insurance, social and cultural functions, and status (Moll et al. 2007; Oosting et al. 2014). In SSEA, water and swamp buffaloes are equally important as cattle for milk production and tilling of rice fields, and the same is true for camels in parts of Africa and Asia (Hoffmann et al. 2014).

Sheep and goats: Sheep and goats, together referred to as small ruminants, are important livestock species for poor people (Udo et al. 2011), but the income derived from keeping sheep and goats is relatively low. Sheep and goats are, therefore, mostly kept in extensive systems. Goat and sheep populations in Africa and Asia are growing by approximately 2.5-3.5 per cent per annum for goats and by 1.1 per cent per annum for sheep, which is slightly higher than the growth of cattle populations on both continents (Mazhangara et al. 2019). Goats and sheep are mainly kept for meat, have a key role in religious festivities, and are an important small capital asset to be sold to meet cash needs.

Pigs and poultry: Pigs and poultry are monogastrics, which implies that they need better-quality feed than ruminants. Pigs and poultry are kept either in backyard systems, where they scavenge their own feed, supplemented with household wastes, or in intensified systems, which require investments in housing, feed and disease control. In low- and middle-income countries, intensive pig and poultry production are the most rapidly growing livestock sectors and are seen as the major future supplier of ASF (Herrero et al. 2013).

Fish: Aquaculture in inland ponds is a growing contributor to the world supply of ASF. Fish farmed in ponds consist mainly of herbivore, omnivore and filter-feeding species. This feeding behaviour allows the inclusion of plant-based by-products in the feed (Hua et al. 2019). Ponds are not only production systems but also complete ecosystems, in which algae and bacteria grow on nutrients and energy from waste streams, contribute to water purification and supply natural foods. Today, the majority of fish in ponds are fed formulated pelleted feeds (Tacon 2020), constituting the main source of waste, besides crop residues, livestock manure or kitchen waste applied to complement pelleted feed (Pucher and Focken 2017). The sediment of fish ponds, where a large proportion of input nutrients accumulates, may be used as a crop fertilizer.

2.2 Farming systems with farmed animal species

The geographical distribution of farmed animal species and farms is not random. The World Bank (2019) considers different combinations of farming systems and farmed animal species associated with different locations in the world. For the present review, the following four combinations are relevant (Oosting et al. 2014; World Bank 2019):

Dryland grazing systems: In dryland regions, mobile grazing systems with pastoralists herding ruminants are dominant. Dryland regions are too dry for crop production, and herding is the only agricultural activity supporting livelihoods. Because of the harsh conditions in dryland regions, human and livestock population densities are low. Pastoralist herding systems are extensive and have a low production per animal; consequently, products come with a high emission intensity. In line with Udo et al. (2016), the emissions of pastoralist herding systems should not be allocated to the ASF produced by ruminants only, but also to the other functions and services they provide. Such functions and services can be cultural (e.g. maintaining rare animal breeds), ecological (e.g. contributing to the dynamics of natural grasslands) and agricultural (providing manure to crop farmers) (Ayantunde et al. 2011; Tamou et al. 2018). Traditionally, pastoralist systems exist in symbiosis with crop systems, in part because of exchange of food, but also because pastoralists require grazing on crop residues during the dry season, whereas crop farmers benefit from manure deposited during grazing (Ayantunde et al. 2011; Tamou et al. 2018; Zoma-Traoré et al. 2020).

Semi-arid to semi-humid grazing systems: In regions with semi-arid to semi-humid conditions, animal rearing is generally limited to grazing ruminants for meat production. These regions could potentially be used for crops or were once covered by forests. Soil depletion after deforestation and use as crop land may have caused the current situation where extensive ruminant production on grassland is the only possible economic activity. Meat production is often a two-stage activity: the first stage consists of a relatively long pre-fattening period with low growth rates on relatively poor pastures, hence with relatively high GHG emission intensities, and then a second stage of intensive fattening at feedlots. Such feedlots are landless systems where beef animals have a high growth rate, hence with relatively low emission intensities, but with high levels of nutrient accumulation and, consequently, high risk of N and P pollution. Moreover, fattening at feedlots requires high levels of feeds produced on land suitable for crop production (Poore and Nemecek 2018; World Bank 2019).

Mixed crop-livestock and aquaculture systems: Because of relatively favourable conditions, these systems are found on farms in relatively densely populated regions, where farms are small. High levels of integration between activities on a farm are observed; various species of livestock are kept to feed on residues of crop production and household wastes, in addition to collected grass or grazing on communal and public lands. Manure is used as a nutrient input for fish production in ponds (Phong et al. 2010), the sediment from which may be used for fertilization. Animal productivity is low, hence the GHG emission intensity is relatively high, but part of the emissions should be allocated to non-ASF production functions of animals such as facilitation of crop production (manure, traction and store of cash) and livelihood support (store of wealth, status, insurance) (Moll et al. 2007; Udo et al. 2016). Intensification of mixed crop-livestock and aquaculture systems may lead to specialized farms that may be characterized as (semi-)industrial systems, since they import the inputs and no longer have crop and other activities on the farm to integrate with. Intensification of mixed crop-livestock and aquaculture systems often affects the feeding management. The required feed quality increases, which reduces the use of waste streams in and between farms.

(Semi-)industrial systems: (Semi-)industrial systems, often with poultry, pigs, aquaculture and dairy, are found in densely populated regions with nearby markets and good infrastructure, allowing farms to source feed externally and market produce with limited transaction costs. Productivity is high, hence GHG emission intensities are relatively low. Industrial systems use high-quality feeds (e.g. maize and soybean – often as soybean meal); consequently, land and water use for such systems compete with human food crop production. Deforestation in Latin America to produce soybean for intensively farmed animal production in Europe and Asia goes beyond food-feed competition. It leads to loss of biodiversity in a global biodiversity hotspot, it releases sequestred carbon into the athmosphere, thus contributing to climate change, and the agricultural practices often result in soil degradation (Pacheco et al. 2021). Moreover, industrial farms risk polluting the environment with N and P. Uwizeye (2019) reported that, with a contribution of 76 per cent, feed production is the primary contributor to total N losses, whereas losses from pig housing and manure management contribute 22 per cent to total N losses, and post-farm activities contribute only 2 per cent.

3. Contribution of farmed animals to circular food systems

At present, farmed animals play an important role in the circularity of food systems in tropical regions. Scarcity of feed inputs and fertilizers makes crop residues, agro-industrial by-products and manure valuable inputs in most farming systems. This section reviews the contribution of the combinations of farmed animals and farming systems described above to circular aspects of food systems, using several specific cases as examples. It focuses on ASF supply, GHG emissions and the performance of these systems within circular food systems, outlined above.

3.1 Ruminants in grazing systems (dryland, semi-arid, semi-humid)

Pastoralist herding systems

Traditional pastoralist herding systems are found in regions where production of human food crops is not possible for biophysical reasons. Hence, there is no direct competition for land use with human food crop production. Regarding avoidance of wastes, pastoralist herding systems exploit dryland grazing areas and the biomass growing there. If not grazed, the biomass will turn dry and not be used. Pastoralists have extensive traditional ecological knowledge about using land and water in a way that is in line with the natural dynamics in these regions.

Regarding recycling of waste, in the dry season the pastoralists' herds provide manure to crop lands while grazing crop residues. Hence, pastoralist systems use animals for what they are good at – i.e. turning low-opportunity-cost biomass into valuable food.

Present-day developments, unfortunately, put enormous pressure on pastoralist systems. Crop land regions are being used more intensively, often through use of (subsidized) synthetic fertilizers, which severely reduces the value of manure for crop farmers. Grazing of crop residues either becomes unavailable or can only occur with payment (Rao et al. 2021). Traditional trekking routes become inaccessible due to expanded land use. As a consequence, conflicts between pastoralists and crop farmers become frequent, overgrazing of grassland regions occurs, and vulnerability to climate change increases (Ayantunde et al. 2011; Rao et al. 2021; Tamou et al. 2018). Prioritization of crop production near regions with pastoralism, therefore, may have very negative effects on the circularity of the combined food systems in the region and makes part of the food system unsustainable. Re-establishing the symbiosis between crop farmers and pastoralists could be a way to achieve sustainable development.

Silvopastoral systems in LAC

In semi-arid to semi-humid regions, where beef production occurs on lands that could potentially be used for crop production or forest, land degradation is a risk. In many parts of the tropics, almost 80 per cent of forests are cleared to establish extensive pasture dedicated to animal grazing with low stocking rates (McGroddy et al. 2015). For instance, in Colombia the expansion of agriculture for grassland was and is one of the main drivers of deforestation (Dávalos et al. 2014; Graesser et al. 2015). Cattle are managed in large paddocks with a stocking rate of approximately 0.6 animals ha^{-1} (Teutscherová et al. 2021). Pasture productivity is low, and seasonal rainfall, continuous grazing and compaction of soils may result in land degradation (World Bank 2019). Silvopastoral systems (SPSs) have been proposed as a sustainable alternative to traditional grassland systems (Somarriba et al. 2012; Tapia-Coral et al. 2005) in Latin America. SPSs are a type of agroforestry considered by the Food and Agriculture Organization of the United Nations (FAO) as a climate-smart agricultural practice (Harvey et al. 2014) that also meets some of the circularity cornerstones: SPSs only minimally compete with food crop production, since they are on land unsuited for crop production, or they even make food crop production possible on previously degraded land, they avoid wastes by making degraded land productive again, and animals are being used to unlock biomass unsuitable for direct human consumption.

SPSs combine cattle, fodder plants such as native or introduced grasses and legumes, and trees and shrubs (native, timber, fruit, legumes) for animal nutrition and complementary uses such as windbreaks, shade, timber, and fruit for household consumption or income generation (Murgueitio et al. 2011; Solorio et al. 2011). SPSs may have diverse settings such as dispersed trees, tree-alley pasture, fodder banks, and pasture with live fences and windbreaks. Under relatively favourable conditions, SPSs may include food crop production in a mixed crop-livestock system (Chará et al. 2019; Pezo et al. 2008). Compared with traditional grassland systems, SPSs present higher forage productivity, which improves the quantity and quality of the diet, improving animals' welfare and productivity, and stabilizing reproductive parameters over time (Dagang and Nair 2003; Yamamoto et al. 2007). Better nutritional conditions have been shown (Chará et al. 2009) to reduce CH_4 enteric emissions by 21 per cent and N_2O emissions by 36 per cent. At the same time, high-quality food available from SPSs throughout the year (Broom et al. 2013; Feliciano et al. 2018) could contribute to reduced need for land conversion and deforestation (Luedeling et al. 2014; Matos 2011; Mbow et al. 2014).

In these SPSs, animal welfare is also improved. The incorporation of shrubs and trees reduces air temperature by 2-3° C and soil surface temperature by as much as 13° C (Cubillos et al. 2016). Shade from the trees has many beneficial effects: lower cattle skin temperatures, and less sun exposure, which reduces sunburn, cancer and photosensitization (Rowe 1989). Increased biodiversity and the number of natural predators lower the populations of ticks and harmful insects, and the incidence of diseases, which leads to a reduction in the use of insecticides and antibiotics.

SPSs have a positive effect on carbon sequestration and, consequently, on GHG emission mitigation, since they increase above- and below-ground biomass and reduce soil erosion (Lorenz and Lal 2014). In dry tropical conditions in Mexico, López-Santiago et al. (2019) reported that SPSs contained more above-ground biomass (approximately 40 Mg dry matter (DM) ha^{-1}) than grass systems (< 10 Mg DM ha^{-1}), and greater below-ground biomass (approximately 16 Mg DM ha^{-1}) than deciduous tropical forest and grass systems (approximately 8.4 and 1.4 Mg DM ha^{-1}, respectively).

Pruning, N-binding through leguminous trees and forages and other management practices may contribute to the build-up of soil organic matter (SOM) (Murgueitio et al. 2007). Besides contributing to carbon sequestration, increased SOM improves soil water-holding capacity, among other properties such as cation exchange capacity, porosity and infiltration.

SPSs can provide benefits to farmers by enhancing nutrient cycling, fodder production for animals, and diversification of income (Ibrahim et al. 2011; Yamamoto et al. 2007). The incorporation of leguminous species such as *Leucaena leucocephala* or fodder banks with legumes enhances symbiotic N fixation (from 52 kg to 400 kg N ha^{-1} $year^{-1}$ depending on the variety, density and environmental conditions (Cubillos et al. 2016; Murgueitio et al. 2007). N-fixation, SOM contribution and a homogeneous distribution of animal excreta and urine contribute to increasing the efficiency of the system in the use and recycling of nutrients. Intensive rotational grazing management practices in SPSs result in a better use of the available forage species and the development of denser sprouts with a higher proportion of leaves and lower fibre content (Senra et al. 2005). As a result, SPSs could increase system productivity – i.e. SPSs enhance livestock productivity up to four times compared to conventional, extensive livestock systems (Montagnini et al. 2013). In addition, because of the integration and recycling in the system, SPSs are relatively independent of external agricultural inputs such as inorganic fertilizer and concentrates (Anguiano et al. 2012; Yamamoto et al. 2007). In summary, SPSs are a circular restoration intervention with positive effects on food production and environmental impacts.

3.2 Fish in pond aquaculture

Pond aquaculture may have three manifestations of circularity at three scale levels: within the pond, within the farm (often mixed crop-livestock systems with fish), and within the broader food system. Inland and coastal ponds are the major fish farming systems in SSEA, accounting for more than 75 per cent of global farmed fish and shrimp production (FAO 2020b).

Fish farming in ponds may not directly compete with human food crop production. Many ponds are fertilized with leftovers, manure and kitchen waste. An example are the semi-intensified systems in Bangladesh (Belton and Azad 2012) that produce fish by application of a combination of organic fertilizer, kitchen waste, home-made feed from local agricultural by-products, and commercial feed (Henriksson et al. 2018; Jahan et al. 2016; Mamun-Ur-Rashid et al. 2013). Commercial feeds produced in Bangladesh account for about 2 million metric tonnes (Mamun-Ur-Rashid et al. 2013), and 90 per cent of the ingredients are by-products from other agricultural activities (Kabir et al. 2017; Mamun-Ur-Rashid et al. 2013). Food-feed competition, therefore, is still rather limited. However, when aquaculture systems intensify more, recycling of waste streams in the ponds can still provide 40-60 per cent of the nutrients required for fish to grow (Kabir et al. 2019). The remainder has to be imported, and, if intended for high productivity, should be of high quality (Boyd 2015), which increases risk of feed-food competition.

Examples of recycling of leftover and waste streams are found in the integrated farming systems of the lower Ganges delta in Bangladesh, and the lower Mekong delta in Viet Nam. Here, unique systems have developed in which rice, fish and shrimps are grown is a circular way (Berg et al. 2012; Bosma et al. 2012; Faruque et al. 2017), sometimes combined with vegetable production on pond or paddy dykes (Karim et al. 2014). On such farms, 30-40 per cent of the farm area is dedicated to trenches to store water that helps in dry season irrigation water management. This water area is used for fish production. Depending on the location, such farms can include freshwater shrimps along with fish. Dissolved/run-off fertilizer from the fields enters the trench and allows growth of algae and other natural food, which is the main nutrient of the fish. During the wet season the fish encroach in the paddy section, and the faecal waste released in the paddy field works as fertilizer for the rice as well. At the end of each culture cycle, the sludge at the bottom of the trench is taken out and used in the vegetable beds on the dykes of the farms. When vegetables are harvested, the roots are often worked into the soil of the paddy field by ploughing; in addition to nutrients, water resources are also shared in this integrated rice-aquaculture system. The inter-crop dependency improves food quality and safety. For example, farmers in Viet Nam are now careful in using pesticides in the rice crop, to avoid the risk of harming the fish or shrimps (Berg et al. 2017), while in Bangladesh vegetables grown on the pond dykes are produced free of chemicals (Faruque et al. 2017). This circularity not only brings efficiency in resource use but also improves product quality and safety.

Some of the production models from SSEA have been piloted in several SSA countries. A pilot of a rice-aquaculture model in the inland valley swamp of Sierra Leone enhanced circular use of agricultural waste and by-products; fish were produced as an additional animal protein, which increased profitability (Sankoh et al. 2018). However, vegetable production on the pond dyke was not successful, as the pond water level dropped quickly with the summer heat, making it difficult to provide enough moisture for vegetable production (Siriwardena et al. 2017).

The projected increase in global fish consumption drives intensification of pond farming, since an increase in pond area will be at the expense of potential human food crop land or waterbodies with fragile biotopes. In such intensified pond systems, feed is formulated based on the nutritional requirements of the fish. The nutrient composition of fish waste is not always ideal for complete mineralization of the waste through natural cycling. Not all the nutrients are used, and accumulation of N in the pond may result in poor water quality and emmision of the GHG nitrous oxide. In addition, accumulation of organic carbon and nutrients such as N and P may occur in intensified fish ponds and eventually lead to pollution when discharged without treatment. By paying attention to the waste composition resulting from feeding during feed formulation, the recycling of nutrients within the pond can be enhanced, which leads to a higher efficiency of nutrient use within ponds, reducing nutrient requirments and contributing to circularity (Kabir et al. 2020).

Presently, the aquaculture feed industry is increasing the use of low-cost, locally sourced inedible parts of food crops that provide fewer nutrients and are less digestible. The loss in essential nutrient (e.g. minerals, trace elements, vitamins, essential fatty acids and amino acids) availability is compensated by directly including the deficient nutrients as additives in the feed (Boyd et al. 2020). Together, with the recycling of wastes through the pond food web, this allows pond farming to reduce nutrient losses and recycle by-products, unlocking biomass that humans do not eat.

During the last decades, aquaculture has become better integrated into the global food system (Naylor et al. 2021) and has made significant contributions to reducing malnutrition by providing essential amino acids and fatty acids (Castine et al. 2017). Aquaculture has also responded to public pressure to improve its environmental performance, by reducing pollution, fish meal and fish oil (Naylor et al. 2021; Hua et al. 2019), and reusing food wastes in aquaculture feeds. By becoming better integrated into the global food system, aquaculture has also made significant contributions to food security, bringing people out of poverty and developing smallholder-inclusive value chains (Hernandez et al. 2018; Pant et al. 2014; Toufique and Belton 2014). In addition, aquaculture is highly diverse, culturing more than 450 species, providing highly diverse foods and nutrition, often imbedded in the local food culture (FAO 2020b).

3.3 Land-limited dairy production in Indonesia

A case study of dairy farming in Lembang subdistrict in West Java illustrates aspects of circularity in small-scale semi-industrial systems, focusing on feed and manure management. Situated on the densely populated island of Java, dairy farming mostly takes place on small-scale, specialized commercial farms in a peri-urban context. The average farm in Lembang has four stall-fed dairy cows and 0.3 ha of land for production of forage and sometimes food crops. Annual production is about 4,500 L per cow per year. The feed ration consists of about 55 per cent agro-industrial by-products (mainly tofu waste, cassava pomace, imported wheat pollard, palm oil meal and corn gluten feed), about 15 per cent crop residues (mainly rice straw), particularly in the dry season when grass is scarce (De Vries et al. 2019), and grass. Grass, the only primary crop in the ration (25 per cent of total DM intake), is collected from roadsides (about one third), grown in state-owned forest areas (half) or grown on slopes too steep for food crop production. Only 15-20 per cent of grass intake (less than 6 per cent of DM intake) is grown on land potentially suitable for cultivation of food crops. In this system, food-feed competition for land is thus limited, and use of by-products and crop residues is relatively high. Moreover, the peri-urban location of dairy farms leads to short transportation times, enabling low post-harvest losses of milk. Development of the sector towards intensification, however, as supported by the Indonesian policy agenda to increase self-sufficiency in dairy production, will increase demand for more and better-quality forages and feeds, potentially threatening food-feed competition.

While dairy cattle in Lembang play a large role in recycling by-products and crop residues, the picture for waste management is less positive. Although most farmers acknowledge that manure disposal is a problem, practical and economic barriers hamper its use. Most dairy farmers in Lembang subdistrict (84 per cent) are disposing of at least some of the manure into the environment, causing pollution of ground- and surface waters, potentially leading to eutrophication of aquatic ecosystems and contamination of drinking water sources (e.g. Budisatria et al. 2007). Only a limited amount is used as fertilizer, mainly because dairy farmers have too little land to apply the manure and because transportation of manure to their own distant fields or to other farms involves significant labour and expenditure. Amounts applied to land near cow barns are extremely high, resulting in considerable run-off and leaching (De Vries and Wouters 2017). Due to the relatively low nutrient content of cattle manure and heavy subsidization of synthetic fertilizers for small-scale farmers in Indonesia, manure is less competitive in terms of macronutrients. So, while using crop residues and by-products as feed unlocks significant amounts of biomass, converting them into high-value dairy products, current manure management practices lead to loss of nutrients and organic matter from the soil-plant-animal cycle.

With regard to GHG emissions, including relatively high-quality by-products in dairy cow rations generally leads to relatively low emissions from feed production and preservation, as most emissions are allocated to the primary product (e.g. grain), and a smaller part to the crop residues (e.g. straw) and the agro-industrial by-products (e.g. pollard). However, feeding cows with by-products may reduce their productivity, as they often have a lower nutritional value than primary products, potentially causing a net increase in total GHG emissions per kilogram of milk. This is illustrated by figure 3 from De Vries et al. (2019), which shows that lower milk yields resulted in higher GHG emissions per kilogram of milk, in line with Gerber et al. (2011). Also, some crop residues and by-products have high embedded emissions from production or processing. For example, De Vries et al. (2020) showed that maize gluten feed as an ingredient of compound concentrate feed increased milk yield but also had a large carbon footprint related to the energy used to dry it. With regard to manure disposal, increasing the use of manure could result in higher GHG emissions, since GHG emissions from manure dissolved in water are lower than when it is stored and applied on-field.

Overfertilization of land close to cow barns causes elevated GHG emissions from nitrous oxide (De Vries et al. 2020).

To enhance the contribution of Indonesian dairy farming to circular food production, manure management should be improved. Locally suitable, low-cost solutions to manage the manure, however, are still mostly lacking. Coupling livestock to land is a proposed solution to increase on-farm manure application (World Bank 2019), but land on the densely populated island of Java is scarce and fragmented. Use of cattle manure in other agricultural sectors is being explored (e.g. Al Zahra et al. 2021; Pronk et al. 2020). In this context, reducing subsidies on artificial fertilizer may be an incentive for increased use of manure as a crop fertilizer. With regard to feeding, in the quest for higher-quality forages and feeds, possibilities to use or upgrade by-products need to be explored – for instance, using technical solutions to improve the nutritional quality and digestibility of (rice) straws (Gerber et al. 2013). In addition, more efficient use of current feed resources can enhance the contribution of dairy farming to circular food production. This can be achieved through improved forage production and conservation, better feeding practices (e.g. drinking water provision), and feeding according to individual animals' nutritional requirements ("balanced rations"). More efficient feeding has no trade-offs, and will benefit both GHG emissions and the efficiency of resources such as land and nutrients.

We close by discussing food system outcomes in this case study of small-scale semi-industrial systems. The land-limited character and high use of crop residues and by-products results in a relatively high productivity of ASF per hectare, with relatively low GHG emissions per kilogram of milk. The smallholder character of dairy on Java demonstrates its inclusiveness for smallholders, provided asset conditions are met (Aune and Bationo 2008; Udo et al. 2011). Strong cooperatives and peri-urban location enable smallholder farms to be linked to input and output markets. Moreover, the number of female and young farmers is relatively high. The main weakness in the circularity of the current system is the poor manure management, resulting in loss of nutrients and ecosystem pollution. Food-feed competition may be threatened when the dairy sector develops towards using more and better-quality forages and feeds.

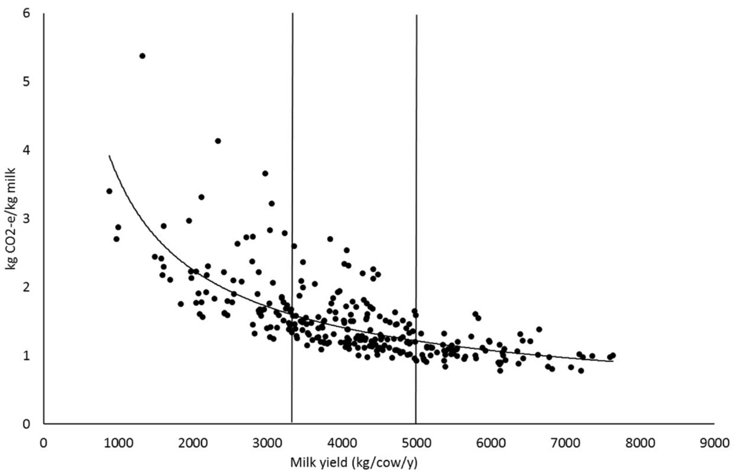

Figure 3: Relation between GHG emission intensity and milk yield per dairy cow in Lembang district, Indonesia

Source: De Vries et al. (2019)

4. Novel protein sources

Novel protein sources, such as insects and micro and macro algae, can contribute to future food supply (Parodi et al. 2019). In line with biomass use from waste streams, novel protein foods should be prioritized for direct human nutrition, and waste streams of novel protein production should be used as feed for farmed animals. Nevertheless, novel protein sources have not yet been incorporated into human nutrition to a large extent, which implies that, at present, the benefit of novel proteins could be that they provide new and sustainable sources of farmed animal feed. The examples in this chapter will shed light on aspects of the use of novel protein sources as ingredients of high-quality feeds in semi-intensive and intensive farmed animal production. Production of novel protein sources for such feeds could be based on recycling of waste streams, with limited land use, and low GHG emissions and N and P pollution. Hence, novel proteins could be a means to meet the triple objective of increased ASF output through intensification of production, environmental impact mitigation and minimal food-feed competition.

4.1 Production of insect protein for feed in East Africa

As a novel protein source, insects are potential contributors to circular food systems because they can convert wastes from many sources into food and feed. Insects require limited water, nutrients, space and energy, while GHG emissions associated with their production are low (Parodi et al. 2019).

Human consumption of insects is common in various countries in SSEA and SSA, including Uganda. Odongo et al. (2018) found that edible insects were in high demand and that prices were higher than those of beef, pork and poultry. Insect marketing in Uganda is built on extensive supply chain networks of collectors and traders. In Tanzania, insects have traditionally been eaten in the north-west, in the areas around Lake Victoria, where the local population appreciates the longhorn grasshopper (*Ruspolia differens*) as a delicacy (Mmari et al. 2017). In the western part of Kenya, people eat termites and other insects.

Farming of insects can be important for the livelihoods of smallholders, because it may increase food supply, generate cash income for households and communities, and create employment opportunities for poor people (Ayieko et al. 2016; Kelemu et al. 2015). Experiences in commercially growing crickets for human consumption have been gained in the Flying Food project in western Kenya (Flying Food 2020).

There is potential to use insect protein in concentrate feed to intensify the livestock sector. The demand for concentrate feed in Africa is growing. Total concentrate feed production has risen by almost 30 per cent in four years, from 31 metric t in 2013 to 39 metric t in 2017 (Alltech 2018), making Africa the fastest-growing continent for feed production in the world. Concentrate feeds are used in semi-intensive and intensive pig, poultry, aquaculture and dairy production. Concentrate feed production depends on the land area available for production of energy (maize and other grains) and protein ingredients (often soybeans or soybean meal after oil extraction), or on fish stocks, since fish meal is one of the ingredients of concentrate feed. Because of biophysical conditions, Kenya has less potential for crop production than Tanzania or Uganda. Therefore, Kenya imports approximately 80 per cent of concentrate ingredients, mostly from Tanzania and Uganda (Githinji et al. 2009; Vernooij et al. 2018). Nevertheless, Kenya is the leading producer of concentrate feeds in East Africa. with an annual production of approximately 1 million t in 2020 (Alltech 2018). Companies and organizations in Kenya, therefore, attach high importance to alternative feed ingredients that can be produced in Kenya itself. Insect protein can be such an ingredient to replace fishmeal or soybean meal. It is produced in the form of larvae that grow from fly eggs inoculated on waste products. Larvae are harvested before they turn into flies (Parodi et al. 2019).

For the current production of concentrate in Kenya, 160,000 t of protein ingredients are needed, corresponding to approximately 350,000 t of insects (with a protein content of 40-60 per cent). With an assumed efficiency of 2 kg of organic waste needed to produce 1 kg of insect biomass, this would require 700,000 t of organic waste annually. The total amount of waste produced in Nairobi is close to 900,000 t. Hence, if Nairobi were to separate organic and inorganic waste, a considerable part of the insect protein for feed could be produced from its city waste. Production of insects on waste streams and their subsequent use as a feed protein source would substantially lower the use of agricultural land for production of feed ingredients for protein (Mulia and Doi 2019). Comparing insect production to soybean production, by replacing the annual protein needed for concentrate feed in Kenya (160,000 t of soybean), approximately 200,000 ha of land could be spared and used for human food production. Replacing fish meal with insect protein in concentrate feeds would reduce pressure on fish stocks.

Insect production in Kenya is still at an initial stage (Ssepuuya et al. 2017), but several training and development projects have been launched to provide farmers with small-scale equipment to produce insects for their own farm animals or for sale to farmers in the immediate neighbourhood. For example, simple buckets have been developed to store food waste on which black soldier fly eggs grow into larvae, which are usually fed to chickens or pigs (Food and Business Knowledge Platform 2020). Over the past five years, approximately 20 insect farms have started to grow insects in medium-scale industrial production systems. Efforts to process city waste into valuable protein are being undertaken – for instance, in Dar es Salaam, Tanzania (Biobuu 2020) – and are in preparation in Kampala, Uganda (Proteen 2020). A few projects for commercial production have been started so far, such as Biobuu Ltd. (Biobuu 2020).

Constraints for insect production for feed include: (i) limited diversity of insect species for protein production – currently mainly black soldier flies, common houseflies and mealworms; (ii) knowledge gap regarding feeding of insect larvae during cultivation; (iii) controlled housing and climate conditions for insect production; (iv) high production costs; and (v) regulations: since 2017, Kenya has had legislation that allows the use of insect protein in animal feed and the use of manure (which is not the case in Europe); Kenyan regulations focus on producing feed ingredients without heavy metals or microbial or mycotoxins contaminants.

The environmental impacts of protein production from insects is the subject of ongoing research, but Van Huis and Oonincx (2017) and Parodi et al. (2019) concluded that GHG emissions associated with insect protein production are low.

4.2 Novel proteins in fish feeding

Aquaculture is the fastest-growing ASF sector and is expected to contribute significantly to the ASF protein requirements of a growing world population. A major challenge of doubling aquaculture production by 2050 is the limited availability of fish meal. Soybean meal, the most popular alternative to fish meal, is also an edible protein for humans and other farm animals, all competing for the same limited land and water resources. Some of the potential ingredients that could minimize the pressure on the use of conventional protein ingredients are microalgae, macroalgae, yeast, microbial protein and insects.

Microalgae: Microalgae are microscopic algae found in freshwater and marine environments. It is estimated that there are between 200,000 and 800,000 species of microalgae. Microalgae are at the base of the aquatic food chain, responsible for half of the world’s primary production and supporting the supply of 90 million metric t of seafood per year through capture fisheries (FAO 2020b; Muller-Feuga 2000). In addition, microalgae drive the production of molluscs, mainly oysters and mussels, which extract nutrients from the sea, including nutrients deposited into the sea from land due to human activity (Cranford et al. 2013; Reid et al. 2013). Smaller contributions from microalgae include larvae culture of numerous fish and shrimp species. If large-scale production of microalgae at an affordable cost becomes possible, microalgae can be a replacement for fishmeal and fish oil. Currently, most microalgae are produced in industrially operated bioreactors that consume high amounts of energy and water. Microalgae can also be grown on wastewaters from agro-industrial and industrial sources, which have significant organic matter and nutrient contents, thus bringing wastes back into the food production system. Treatment of such waste streams comes with additional costs – for instance, to remove toxins that otherwise bioaccumulate in microalgae (Mohd Udaiyappan et al. 2017) – while energy use and possible GHG emissions should be considered.

Replacing conventional protein in fish feed with microalgae from 0 to 100 per cent consistently increased feed efficiency for carp and catfish, while for more carnivorous freshwater species, the efficiency of feed use decreased with increasing microalgae inclusion level. The replacement of fishmeal with microalgae in shrimp diets had no effect on production. In salmon diets, 50 per cent of fishmeal could be substituted by microalgae protein, while for other marine fish up to 40 per cent replacement did not have any negative consequences for production or feed efficiency (Cottrell et al. 2020; Gamboa-Delgado and Márquez-Reyes 2018; Hemaiswarya et al. 2011; Shah et al. 2018).

Microalgae are produced in large-scale photo-bioreactors. The land area needed to produce fish feed was 10 per cent less for fish feed with microalgae than for a reference diet (Taelman et al. 2013). However, the GHG emissions of microalgae produced in a photo-bioreactor are higher than for a fishmeal-based diet, due to high use of fossil fuel (ibid.). When rearing microalgae in waste waters, there will be a trade-off between the energy required for conventional wastewater treatment versus microalgae production and processing.

Macroalgae: Macroalgae, also known as seaweed, are macroscopic, multicellular marine algae. The protein content in the dry matter of macroalgae varies from 5 to 50 per cent (Wan et al. 2019). The red seaweed *Pyropia sp.* has a protein content of 50 per cent (ibid.), and can replace fishmeal in fish diets. Macroalgae have high levels of highly unsaturated fatty acids. Macroalgae containing less protein might be used as an energy source, replacing terrestrial carbohydrate sources. Seaweed is a popular human food in SSEA, and one should carefully consider which species can be included as a feed ingredient in fish diets, and which species should be consumed by humans. Advantages are that macroalgae are grown entirely in brackish or marine water bodies, and that they can strip excess nutrients from waste waters. Therefore, macroalgae do not compete with arable land, for fresh water or for ingredients used in animal feeds. Because no external nutrient inputs are needed, seaweed will reduce GHG emissions by replacing terrestrial plant sources otherwise used in fish feeds.

Inclusion of seaweed up to 25 per cent in diets for carp, shrimp and non-salmonid marine fish either improves or maintains the feed conversion ratio, compared to a conventional diet. Including more than 25 per cent reduces the efficiency of feed use. For other aquaculture species, inclusion of macroalgae in the diet reduces feed efficiency (Cottrell et al. 2020; Wan et al. 2019).

One major constraint with macroalgae is the presence of non-starch polysaccharides, which cannot be directly digested by fish, only indirectly by micro-organisms present in the gut (Wan et al. 2019). In addition, nutrient content shows seasonal variation, and some species accumulate toxins from waste discharge (ibid.). Therefore, there is a need to develop production methods resulting in safe-to-use macroalgae for fish diets. More research is needed on maximum inclusion levels of seaweed in fish diets, considering a higher degree of variation in quality, and the presence of heavy metals and other contaminants.

Attention should be paid to mass extraction of seaweeds from the ocean. The stores of N and P in the ocean are limited. Mass extraction of seaweeds might reduce nutrient availability for microalgae, which are at the base of the marine food web. If there are fewer microalgae, production at higher trophic levels at sea might decline. Better insights into marine nutrient balances at local or regional level are needed before extracting large amounts of nutrients through seaweed farming (Van der Meer 2020).

Yeast: Yeasts are co-products from the brewing industry. Yeasts contain 45-55 per cent crude protein and can replace fishmeal up to 75 per cent in fish diets without compromising growth (Gamboa-Delgado et al. 2016; Pongpet et al. 2016). Yeasts can also be included in low concentrations as a catalyst in fish diets, improving the efficiency of using plant protein (Li and Gatlin III 2003). Inclusion of yeast increases feed efficiency (Gamboa-Delgado and Márquez-Reyes 2018; Pongpet et al. 2016) and enhances fish immunity against bacterial diseases (Iwashita et al. 2015). Despite its significant potential as a replacement for fishmeal, the price of yeast is still a major challenge.

Microbial (bacterial) biomass: Bacterial biomass is a popular alternative protein source not competing with human food. It can be grown by using agricultural wastes such as fruit pulp and maize stover effluents (Mahan et al. 2018), and even manure (Patthawaro and Saejung 2019). Therefore, microbial protein could play a substantial role in circular food systems and reduce nutrient losses. Microbial protein does not require much land, as it is produced industrially (Ringpfeil 2016). For carp, catfish and salmonids, replacing up to 30 per cent of conventional protein with microbial protein either improves or has no effect on feed-use efficiency (Cottrell et al. 2020; Gamboa-Delgado and Márquez-Reyes 2018).

Insect meal: The feed efficiency for all important commercial fish species is improved or is not affected by the inclusion of insect protein in the feed. Only for non-salmonid marine fish species does inclusion above 60 per cent as a protein source result in a decline in feed efficiency (Cottrell et al. 2020). Limiting amino acids are histidine, lysine and tryptophan, which could be supplemented (Sánchez-Muros et al. 2014), either in the feed or through the pond’s ecosystem. Therefore, insect meal is a potential alternative to conventional protein ingredients. Another advantage is that rearing insects requires minimal land areas, therefore only marginally competing for land use with crops. Its biggest challenge is the price. The cost of insect meal is higher than the conventional protein ingredients used in fish diets.

5. Discussion and conclusions about the role of farmed animals in circular food systems

We have reflected on the role of farmed animal species and farming systems in tropical regions, based on the characteristics set for circular food systems: (i) using arable land and water bodies primarily to produce food for direct human consumption, hence limiting feed-food competition; (ii) avoiding or minimizing food losses and wastes; (iii) recycling by-products, inevitable food losses and waste streams back into the food system; and (iv) using animals to unlock biomass with low opportunity costs for humans into value food, manure and other ecosystem services. In the examples cited, we have paid attention to the contribution of diverse animals in farming systems and their expected development to the food system outcomes of food security and environmental impacts.

The review shows that in relatively traditional systems, such as pastoralist systems and mixed crop-livestock systems, feed-food competition is limited, waste streams are widely used, and livestock is used for what it is good at. It also shows that ASF production in tropical regions faces the need to produce more to feed more people, provide essential nutrients to poor people or meet the demand of the increasing population of urban dwellers (Adesogan et al. 2020; Oosting et al. 2014). To meet this increasing demand, production is intensifying, indicating higher production per unit of land or per fishpond. This has multiple implications:

- For pastoralist grazing systems, intensification implies that traditional exchanges between crop farmers and pastoralists come under pressure. The future of ASF production in regions with pastoralism seems to be in relatively intensive systems in the crop production areas, with seasonal grazing of cattle in the cropping season in the dryland regions by contracted herders. This situation has important social consequences, such as conflicts between herders and crop farmers, and a lack of future prospects for pastoralists. Collapse of the pastoralist system would mean that part of the dryland regions may become underused. It is unknown whether the process of increasing crop farming and marginalization of pastoralism is affecting the total food output of the pastoralist and crop regions together, in terms of both quantity and diversity. Mottet et al. (2017) presented the grassland regions of the world as a basis for livestock production without food-feed competition. They optimistically conclude that a modest improvement in feed-use efficiency in such regions could mean a great contribution to future food supply because the grassland regions cover a considerable part of the globe. Ayantunde et al. (2011) and Oosting et al. (2014), however, argued that the unfavourable conditions – i.e. seasonal rainfall, risk of droughts, aggravated by climate change and the expansion of crop farming and associated societal disconnects – make it very difficult to increase feed-use and land-use efficiency in many grassland regions. Tamou et al. (2018) reported that when technological interventions (i.e. fertilization and/or irrigation) are possible in grassland regions, such interventions result in increased cash and food crop production and not increased animal production.

However, under more favourable conditions (such as in LAC), systems with internal diversity and good management may restore grasslands and even mimic forest systems, contributing to the circularity of food systems. These may make greater contributions to food security and mitigation of climate change than the traditional pasture-based beef production. Nevertheless, the scope for large-scale regenerative, agroecological approaches to agriculture for SSA and SSEA have yet to be explored.

- For mixed crop-animal systems, intensification implies that farms specialize, be it towards dairy, pig or poultry production or aquaculture (Oosting et al. 2014; Udo et al. 2011). Traditional within-farm circular pathways may disappear; the value of crop residues (insufficient quality for the desired production level) and manure (lower fertilization value than, often subsidized, synthetic fertilizer) decreases to the extent that they are regarded as wastes. Crop residues may still have value in intensive farms providing carbon to soils, but manure may be discharged, causing environmental problems such as in the Indonesian example. Intensification in mixed crop-livestock systems generally implies that the systems move in the direction of industrial systems. Use of high-quality feeds to achieve high animal productivity is a characteristic of intensified mixed crop-livestock and industrial systems. Agro-industrial by-products can be sourced to be constituents of such high-quality feeds. However, with increasing intensification and higher total ASF production, the need arises to cultivate feed crops, such as maize and soybean, and forage crops, such as grasses and legumes, on lands that are suitable for human food crop production. Hence, intensification may result in increased feed-food competition.

Since intensification most often results in increased productivity of farmed animals, the emissions of GHG per kilogram of product will reduce (see figure 3). Risk of pollution of the environment by N and P, organic residues and heavy metals may increase under intensification, due to the accumulation of these substances in farms and fishponds and a lack of land to apply it to. Proper waste management and recycling are options to prevent pollution, but the example of dairy farms in Indonesia shows that recycling of manure faces constraints. The World Bank (2019) proposed coupling livestock production and aquaculture at the farm or regional level to reduce transportation costs and make the application of manure to land more likely. In mixed crop-farmed animal systems, animals have multiple functions, many of which are crop-oriented (i.e. provision of manure, draught power, and store of small amounts of cash for seed and other crop inputs), while other functions (status, income provision, ASF, store of wealth) are livelihood-supporting social and economic functions (Moll et al. 2007; Oosting et al. 2014; Udo et al. 2011). To fulfil such functions, having a large number of animals is often better than having highly productive animals. If mechanization and the development of financial institutions could replace some of these functions, there would be less need for smallholders to keep a large number of animals, and a reduced animal population could produce the ASF (Oosting et al. 2014). Reducing the size of the animal population is one of the best ways to reduce environmental impacts. Intensification of ASF production is often not limited to individual farms. Production clusters and value chains are likely to develop. Organizing the supply of high-quality feeds based on agro-industrial waste products and novel protein sources, and of fertilizers produced from wastes, including manure, can be done in such clusters and chains (Van der Lee et al. 2018). To reduce food-feed competition due to intensification of farmed animal systems, novel protein sources could replace traditional ones in concentrate feeds, such as soybean meal and fish meal. This substitution will reduce the food-feed competition for land and water and reduce the pressure on fish stocks. Production of such novel protein sources in itself is land- and water-efficient, but energy requirements for production can be high. The production of novel proteins is still at the innovation stage, and costs are still high, meaning that economic competition with other protein sources is still difficult.

Mixed crop-animal systems traditionally, and particularly when subsistence-oriented, play an important role for poor people and for women. For poor people, this farming system provides a livelihood with limited external inputs, and a high internal diversity, which creates a resilient environment for the farming household. Animals play an important role in these farms. Generally poultry is the type of livestock that is easily accesible to poor people, with small but essential benefits to them, be it for household nutrition, economy or social relations. Smallholder poultry production is, therefore, essential for the food security and livelihoods of many poor people in the world (Alders et al. 2019; Udo et al. 2011).

The role of farmed animals for women depends on social, cultural and economic factors and the species of animal. Cattle are often owned by men, whereas smaller animals are kept by women. Women are often responsible, including for decision-making, for milking and processing the milk, feeding and watering, and caring for young and sick animals. Marketing is often a male task (Rota and Sperandini 2010).

Stepping out of poverty is often associated with moving up the livestock ladder (i.e. via small ruminants and pigs to cattle; Udo et al. 2011) or with intensification and specialization of the farming system. These steps up the livestock ladder and intensification and specialization imply that more inputs are required and that farms become more market-oriented (Oosting et al. 2014; Udo et al. 2011). Consequences are that women and a considerable proportion of poor households may become excluded from the development of farmed animal production. Circularity of food systems supports the subsistence roles of farmed animals and, consequently, the inclusion of poor people and women. Intensification, and other forms of farming aimed at higher food output and fewer environmental impacts, on the other hand, run the risk of exclusion.

In conclusion, in tropical regions farmed animals are important in circular food systems because of their use of land unsuited for crop production, their upgrading of crop residues and their supply of manure for crop production. Nevertheless, the increasing demand for ASF puts pressure on important characteristics of circularity, such as minimizing feed-food competition, maximizing the use of waste streams in feed and of manure for fertilization, and including poor people and women. Hence, in line with conclusions for Western countries (Van Kernebeek 2020; Van Zanten et al. 2019), maximum circularity and sustainability of food systems can only be achieved by optimizing the population size of animals. Hence, achieving a sustainable contribution of ASF to global food security is not only a technical issue or the result of a process driven by economic supply and demand. It is also a governance issue. Public, private and social actors should partner to define and implement policies and practices to achieve sustainable development of farmed animal production within the broader food system (Breeman et al. 2015).

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